

Validation of boxwing models for GNSS satellites

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- Approach
- About the scalable boxwing model
 - Scale Factors
 - Plate Groupings
- Results
- Conclusion

Background

Background

- Radiation Pressure a significant source of error in orbit modeling
 - Solar Radiation
 - Earth Reflected/Emitted Radiation
- New Empirical CODE Orbit Model (ECOM2) [Arnold et al. 2015, J. Geod.]
 - Effective for GPS & GLONASS outside of eclipse season
 - Less effective for Galileo, etc.
- Adjustable boxwing model
[Solano, 2014, PhD Thesis]; [Montenbruck et al. 2015, J. Geod.]; [Montenbruck et al. 2017, Adv. Space Research]
 - Semi-Analytical model for radiation pressure
 - Improved performance during eclipse season

Approach

Approach

- Implement Scalable–boxwing model in development version of Bernese GNSS Software
- Compute scale factors per satellite, plate, etc.
 - Investigate various plate groupings
 - Identify long–term trends in scale factors per SVN
- Analyze improvements over ECOM2
 - ECOM2–only
 - ECOM2–plus–boxwing
 - ECOM2–plus–scaled–boxwing:
 - Satellite–specific, Yearly–average Scale Factors

Scalable–Boxwing Model Definition

Radiation Pressure force calculation per plate:

Without immediate thermal re-radiation: $\vec{F} = -\frac{\Phi}{c} \cdot A \cos \theta \cdot \left[(\alpha + \delta) \vec{e}_{\odot} + \frac{2}{3} \delta \vec{e}_n + 2\rho \cos \theta \cdot \vec{e}_n \right]$

With immediate thermal re-radiation (MLI): $\vec{F} = -\frac{\Phi}{c} \cdot A \cos \theta \cdot \left[(\alpha + \delta) \left(\vec{e}_{\odot} + \frac{2}{3} \vec{e}_n \right) + 2\rho \cos \theta \cdot \vec{e}_n \right]$

Φ = solar flux

c = speed of light

} Constants

A = surface area of plate

α = absorptivity of plate

δ = diffuse reflectivity of plate

ρ = specular reflectivity of plate

\vec{e}_n = unit vector normal to plate

\vec{e}_{\odot} = unit vector towards radiation source

θ = angle between \vec{e}_{\odot} and \vec{e}_n

} Macromodel definition

$$\alpha + \delta + \rho = 1$$

} Attitude geometry

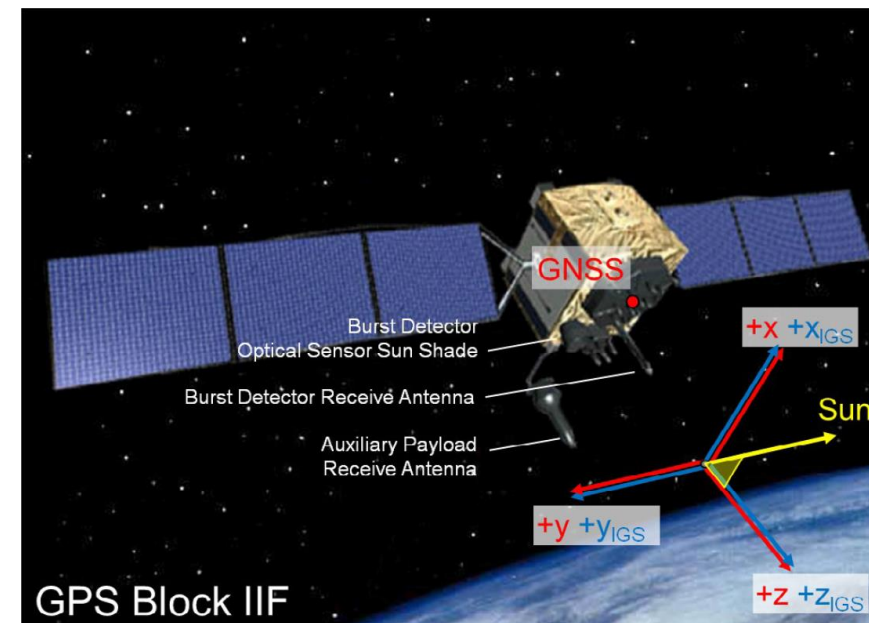
Exact geometry and material properties are not necessarily known. A single scale factor multiplied by the force on a given plate can compensate for uncertainties in all four plate properties.

Scale factors can be introduced as solveable parameters in the least squares model.

Example Boxwing Macromodel & Plate Groupings: GPS

Macromodel Definitions:

- By SV block
 - Example is GPS IIF
- As collection of plates
 - Geometrical and optical properties for each plate
 - Force calculated on any plate where $\cos \theta > 0$ and summed together
 - Only specular and diffuse reflectivity are specified
 - Absorptivity is Calculated



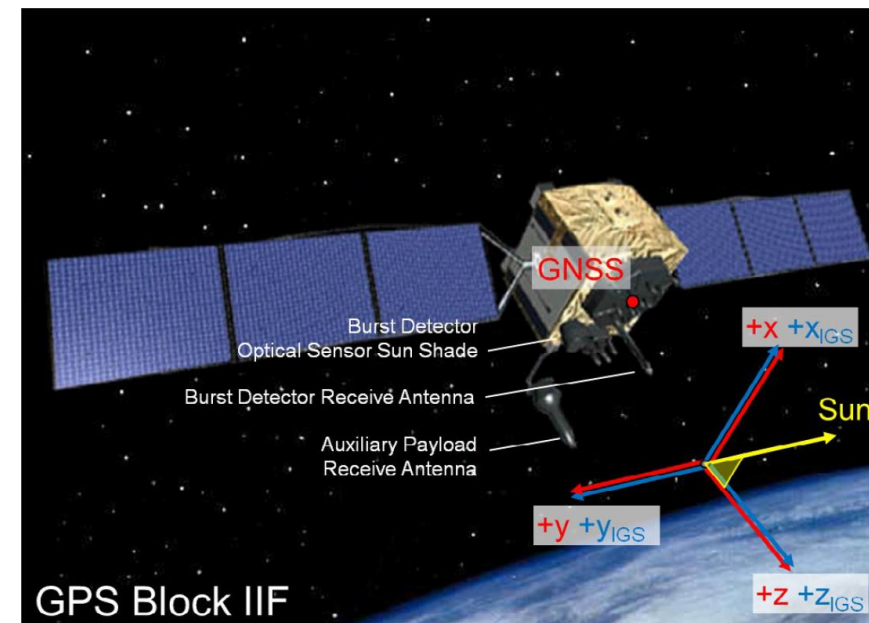
GPS Block IIF
[Montenbruck et al, 2015. Adv. In Space Research]

Multiscale	Plate	Mod	Area (A) [m ²]	Normal (\vec{e}_n)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
	1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
	2	1	5.720	[-1, 0, 0]	0.112	0.448		-X
	3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
	4	1	7.010	[0, -1, 0]	0.112	0.448		-Y
	5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
	6	1	5.400	[0, 0, -1]	0.000	0.000		-Z
	7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0, +1, 0]	Solar panels front
	8	0	22.250	[-1, 0, 0]	0.196	0.034	-SUN: [0, +1, 0]	Solar panels back

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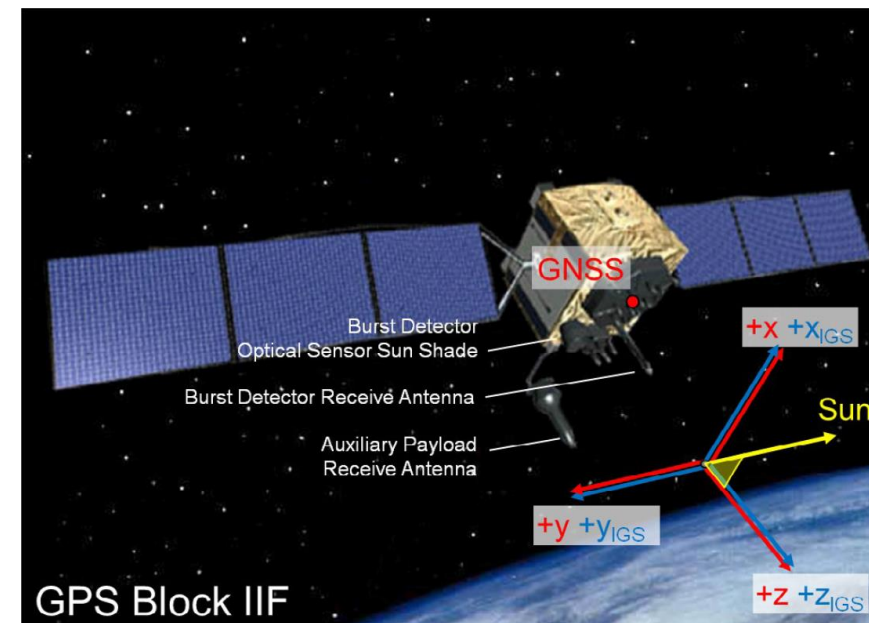
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	5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
	6	1	5.400	[0, 0, -1]	0.000	0.000		-Z
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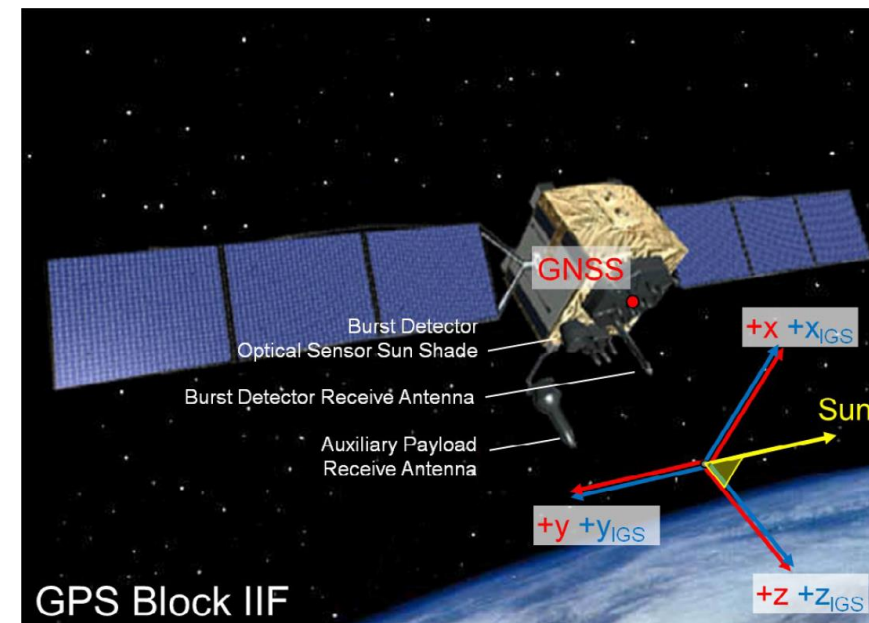
GPS Block IIF
[Montenbruck et al, 2015. Adv. In Space Research]

SmartScale-2	Plate	Mod	Area (A) [m ²]	Normal (\vec{e}_n)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
	1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
	2	1	5.720	[-1, 0, 0]	0.112	0.448		-X
	3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
	4	1	7.010	[0, -1, 0]	0.112	0.448		-Y
	5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
	6	1	5.400	[0, 0, -1]	0.000	0.000		-Z
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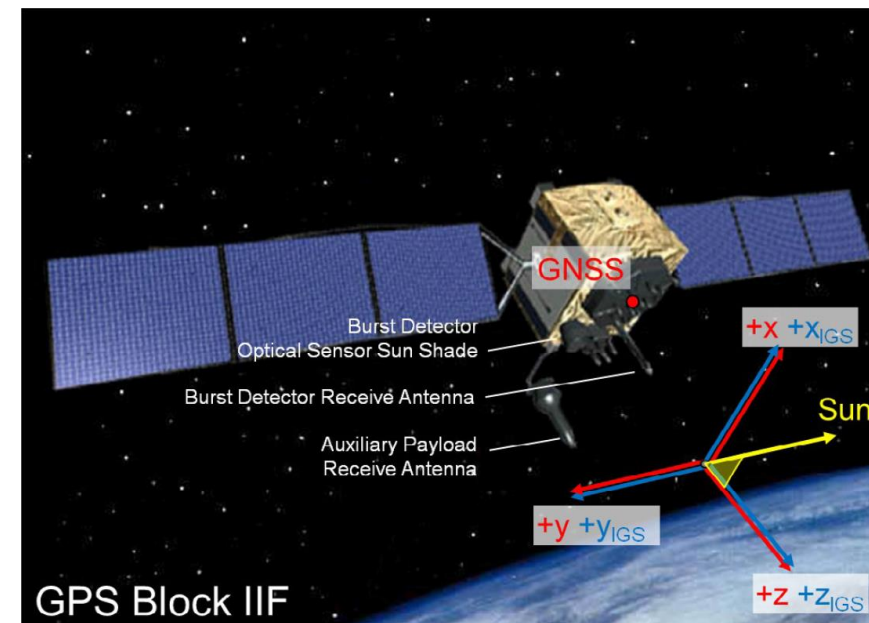
GPS Block IIF
[Montenbruck et al, 2015. Adv. In Space Research]

Smartscale-4	Plate	Mod	Area (A) [m ²]	Normal (\vec{e}_n)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
	1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
	2	1	5.720	[-1, 0, 0]	0.112	0.448		-X
	3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
	4	1	7.010	[0, -1, 0]	0.112	0.448		-Y
	5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
	6	1	5.400	[0, 0, -1]	0.000	0.000		-Z
	7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0, +1, 0]	Solar panels front
	8	0	22.250	[-1, 0, 0]	0.196	0.034	-SUN: [0, +1, 0]	Solar panels back

Example Boxwing Macromodel & Plate Groupings: GPS

Macromodel Definitions:

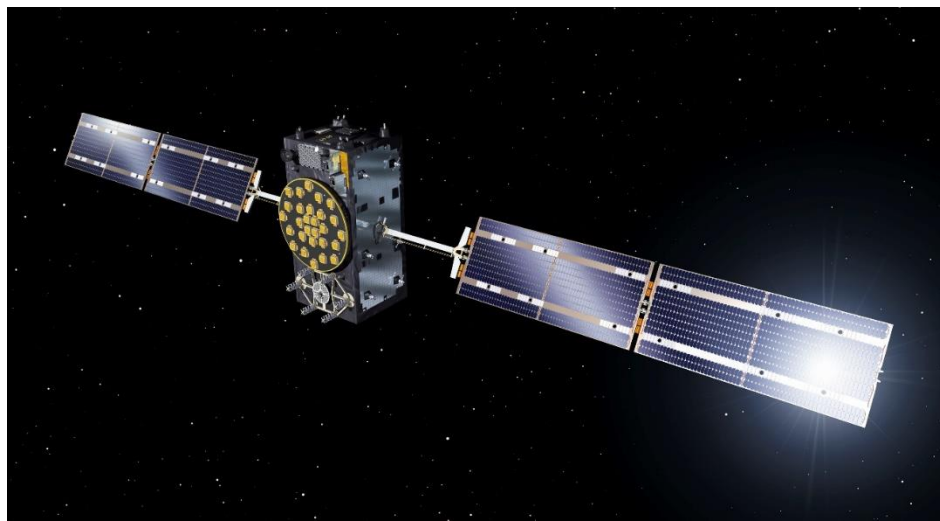
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GPS Block IIF
[Montenbruck et al, 2015. Adv. In Space Research]

Smartscale-3	Plate	Mod	Area (A) [m ²]	Normal (\vec{e}_n)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
	1	1	5.720	[+1, 0, 0]	0.112	0.448		+X
	2	1	5.720	[-1, 0, 0]	0.112	0.448		-X
	3	1	7.010	[0, +1, 0]	0.112	0.448		+Y
	4	1	7.010	[0, -1, 0]	0.112	0.448		-Y
	5	1	5.400	[0, 0, +1]	0.112	0.448		+Z
	6	1	5.400	[0, 0, -1]	0.000	0.000		-Z
	7	0	22.250	[+1, 0, 0]	0.195	0.035	+SUN: [0, +1, 0]	Solar panels front
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Discussion on Thermal re-radiation: Galileo

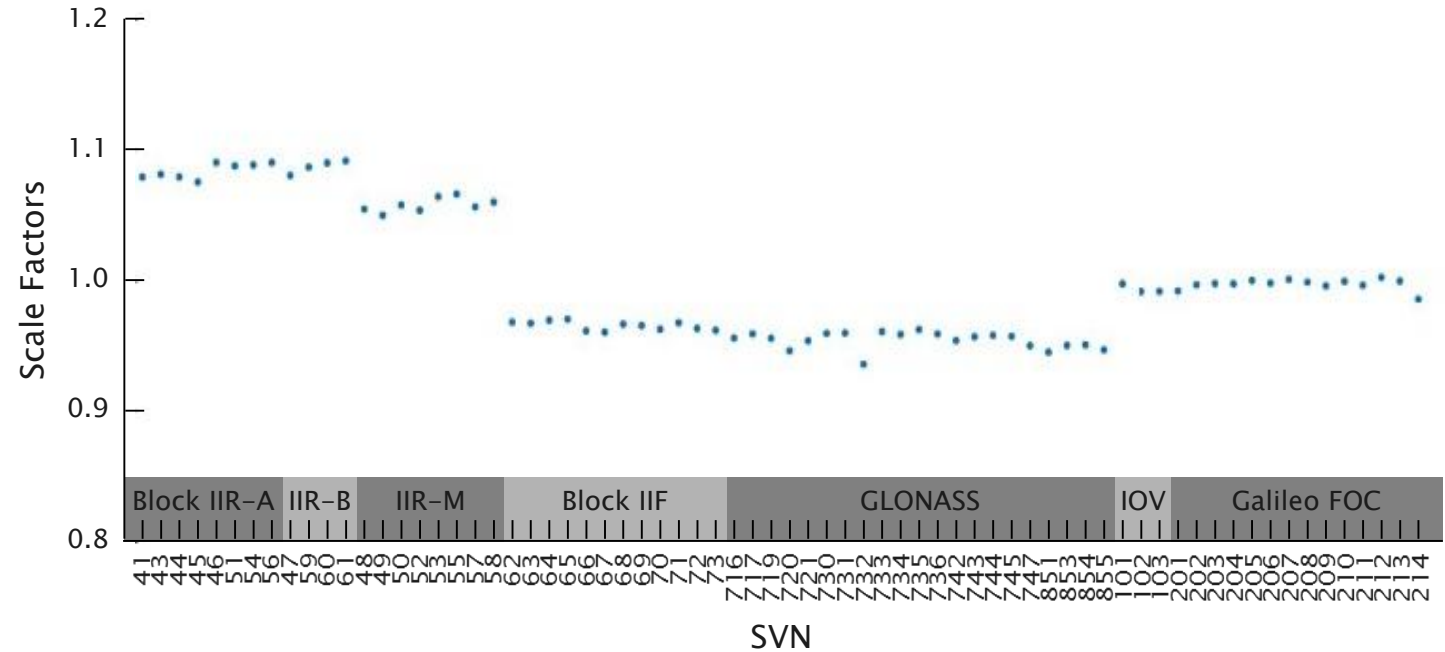
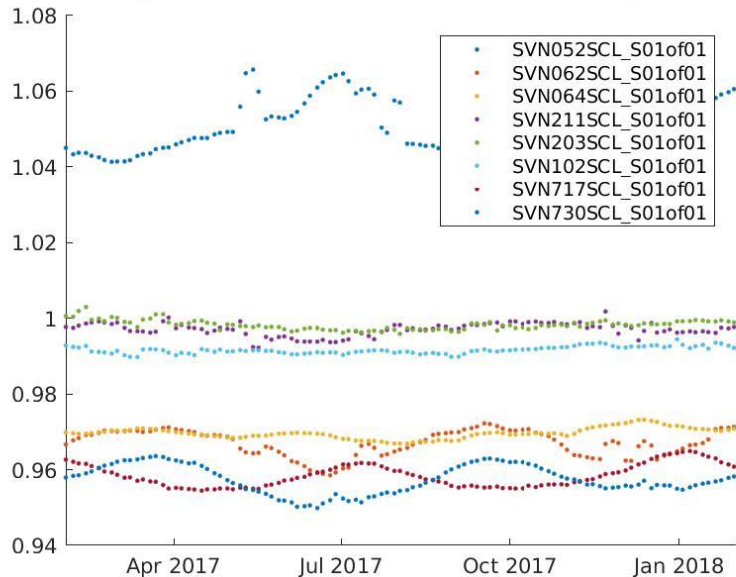
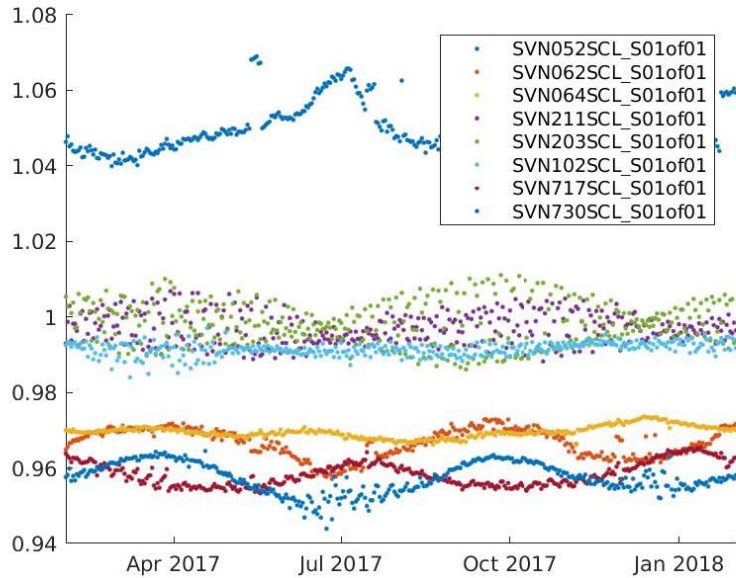


[https://www.esa.int/spaceinimages/Images/2014/07/Galileo_satellite]

- Satellite geometry and optical properties given by GSA
- Front side of solar panel has two different “materials”
 - ~28% of solar panel surface area
 - With immediate thermal re-radiation yields scale factors closer to 1.

Plate	Mod	Area (A) [m ²]	Normal (\vec{e}_n)	Specularity (ρ)	Diffusivity (δ)	Rotation Sys.	Description
1	1	1.320	[+1, 0, 0]	0.000	0.070		-X Material A
2	1	0.440	[-1, 0, 0]	0.000	0.070		+X Material A
3	1	0.880	[-1, 0, 0]	0.730	0.190		+X Material C
4	1	1.244	[0, +1, 0]	0.000	0.070		-Y Material A
5	1	1.539	[0, +1, 0]	0.730	0.190		-Y Material C
6	1	1.129	[0, -1, 0]	0.000	0.070		+Y Material A
7	1	1.654	[0, -1, 0]	0.730	0.190		+Y Material C
8	1	1.053	[0, 0, +1]	0.000	0.070		+Z Material A
9	1	1.969	[0, 0, +1]	0.220	0.210		+Z Material B
10	1	2.077	[0, 0, -1]	0.000	0.070		-Z Material A
11	1	0.959	[0, 0, -1]	0.730	0.190		-Z Material C
12	0	7.760	[+1, 0, 0]	0.080	0.000	+SUN: [0, +1, 0]	Solar Panels Material E
13	?	3.060	[+1, 0, 0]	0.100	0.000	+SUN: [0, +1, 0]	Solar Panels Material D
14	0	10.820	[-1, 0, 0]	0.196	0.034	-SUN: [0, +1, 0]	Solar Panels back

Long-term Trends in Scale Factors: Monoscale

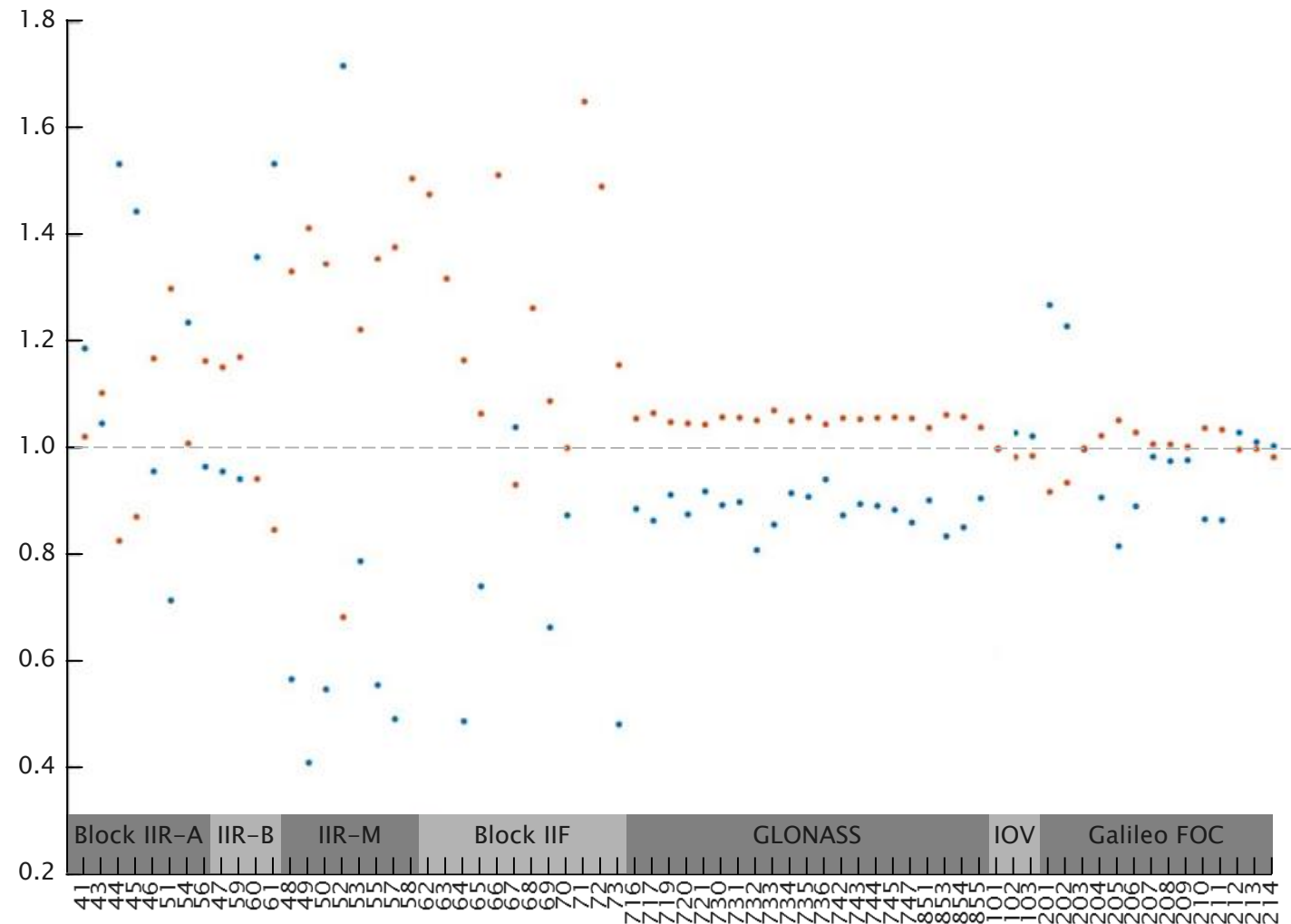


Top Left: Scale factors for selected satellites:
Monoscale model, daily solution, 1-year

Bottom Left: Scale factors for selected satellites:
Monoscale model, 7-day stack, 1-year

Top Right: Scale factors for all satellites:
Monoscale model, 1-year stack

Yearly Scale Factors: Smartscale-2



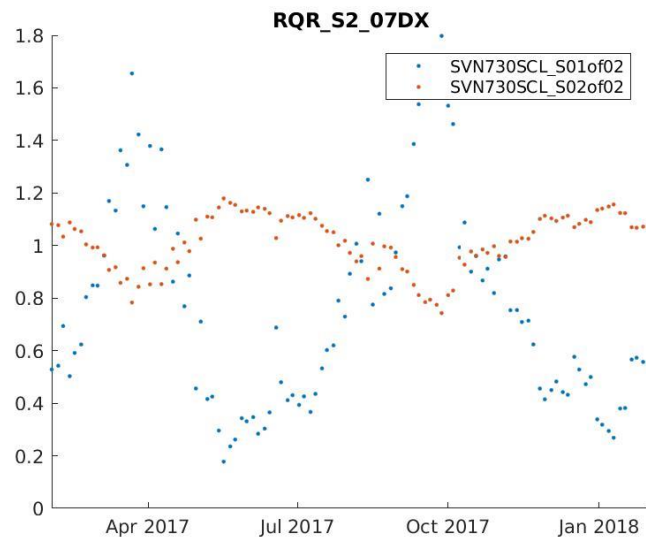
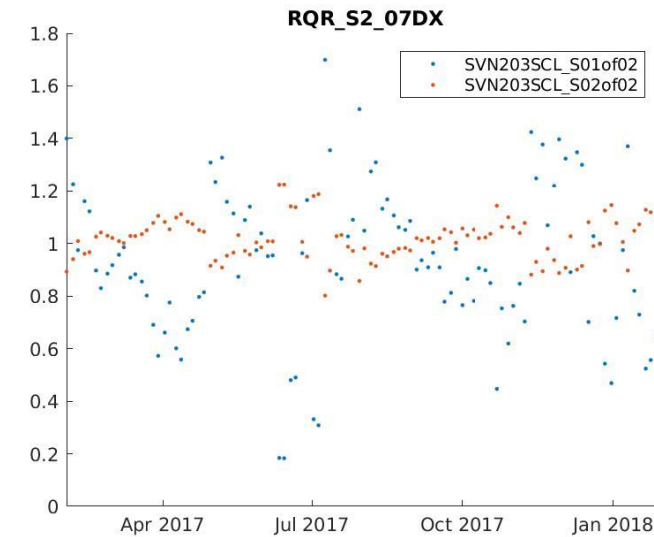
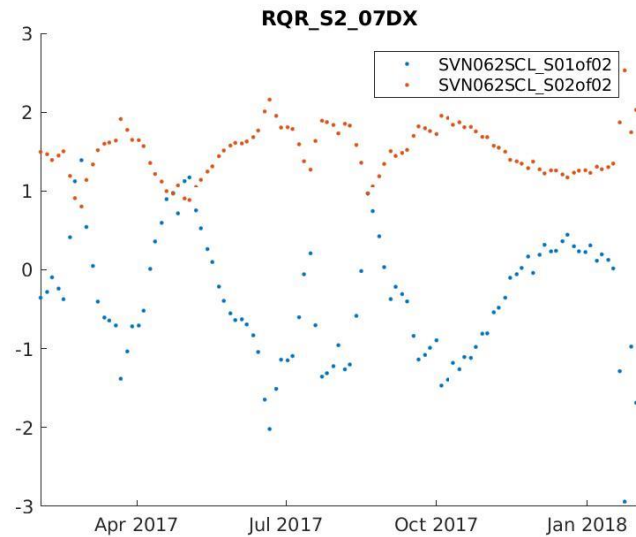
GLONASS & Galileo:
similar scale factors for all
satellites in same block

Scale factors close to 1.

GPS:
more variation between
satellites in same block

Scale factors farther away
from 1.

Long-term Trends in Scale Factors: Smartscale-2



Scale factors for selected satellites:
Smartscale-2 model, 7-day stack, 1-year

Top Left: GPS SVN 62

Bottom Left: GLONASS SVN 730

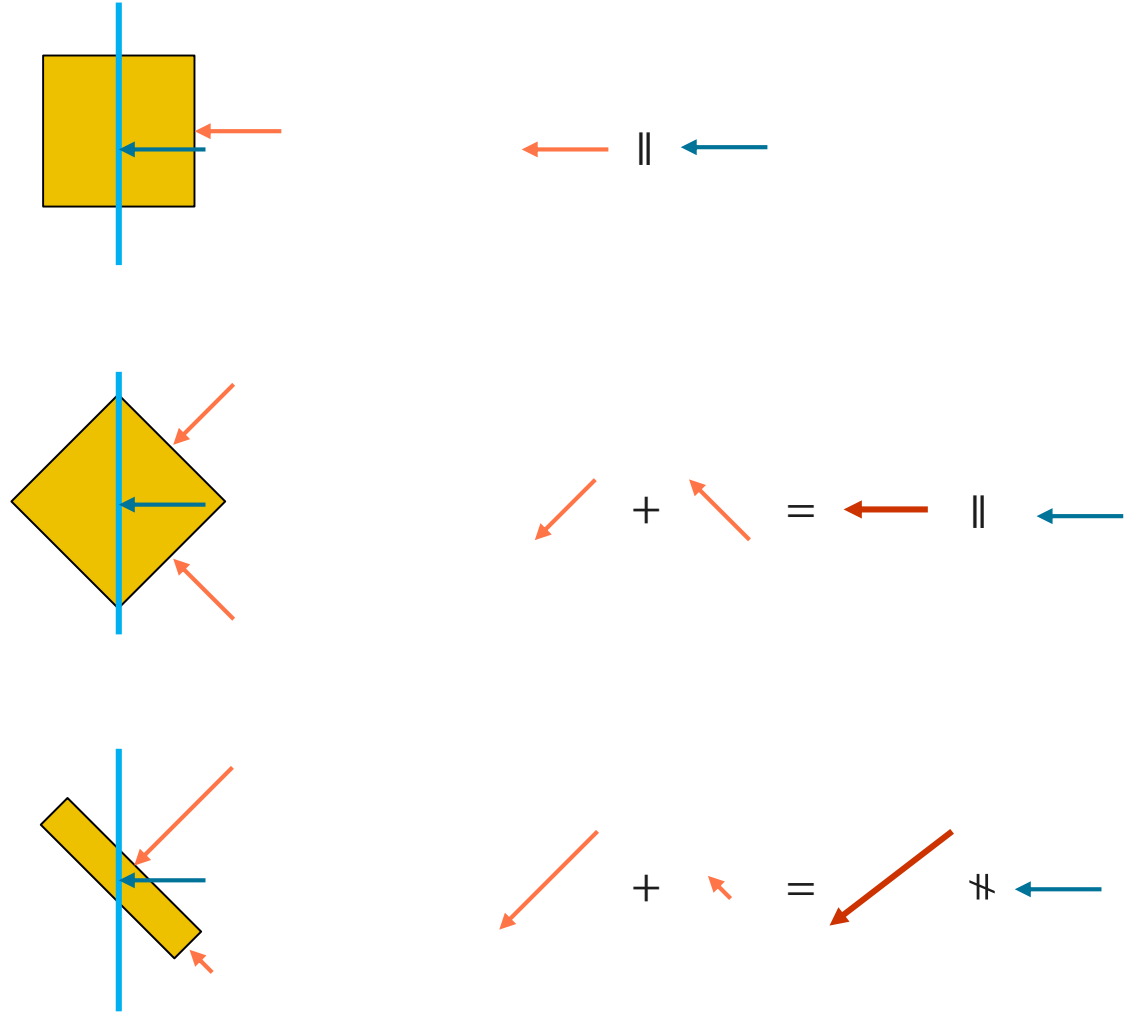
Top Right: Galileo SVN 203

***Note different scale for GPS**

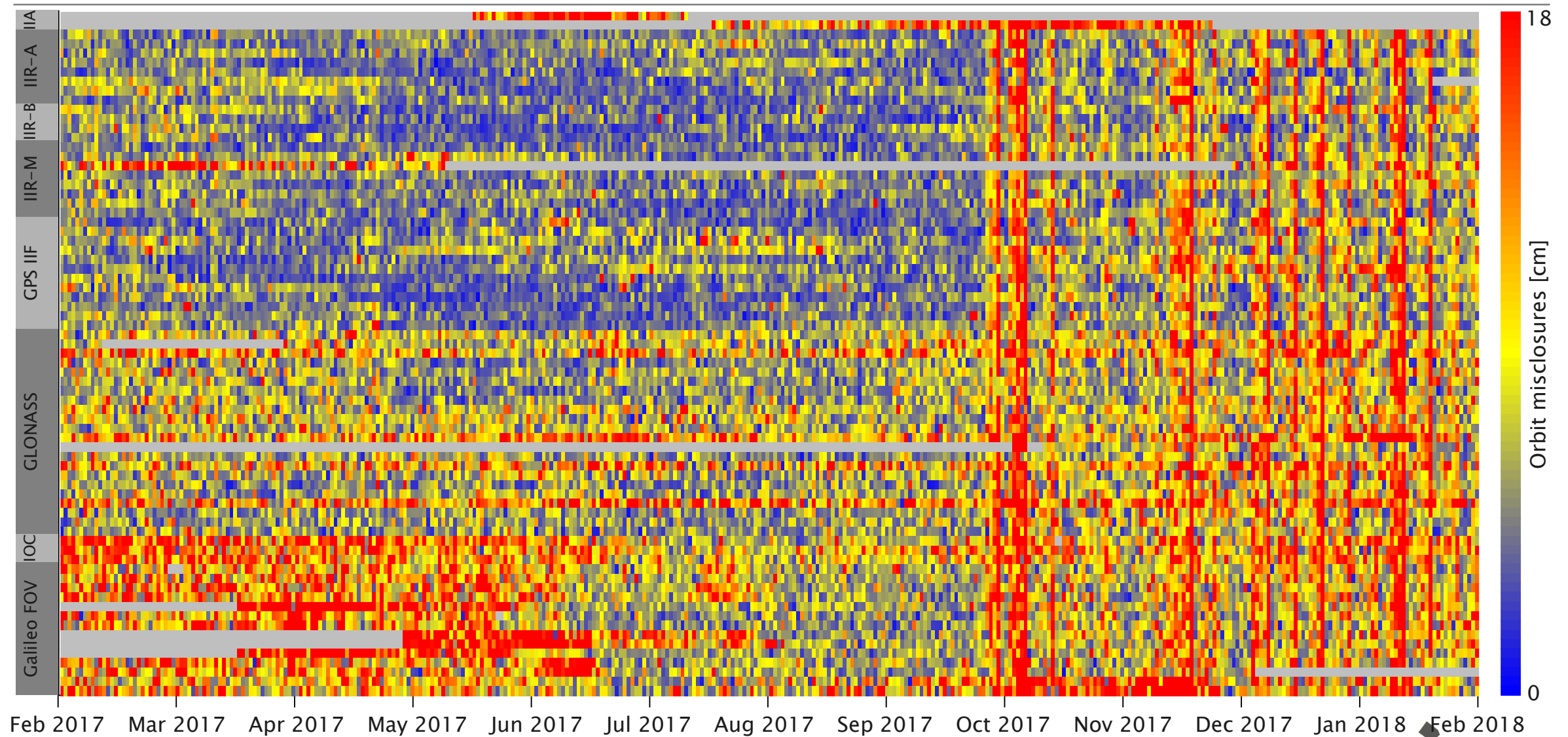
Monoscale vs. Smartscale/Multiscale

Co-variances between scale factors due to:

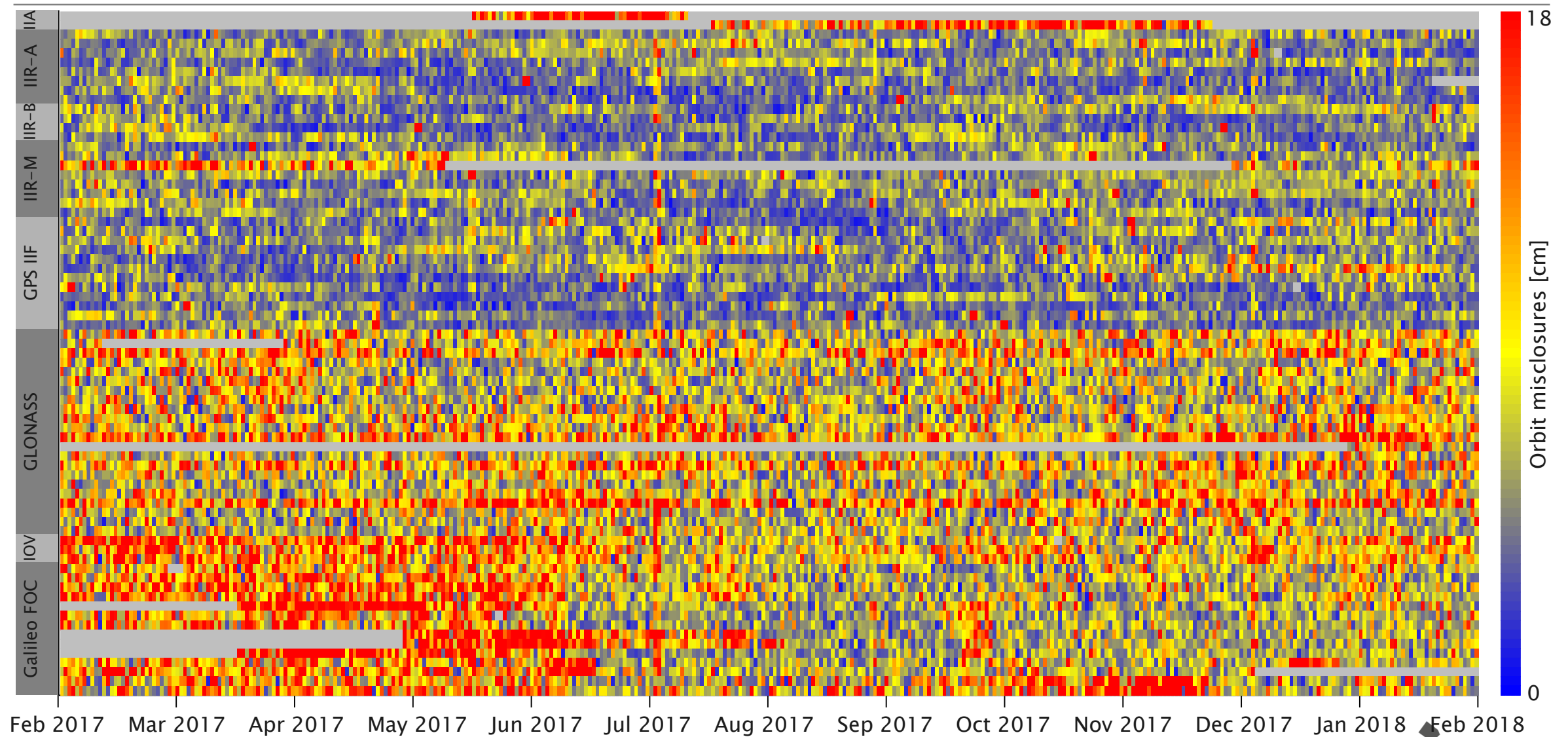
- Similar optical properties
- Parallel plates
- Attitude geometry
- Parallel resultant force



Orbit Misclosures: ECOM-only (1-day solutions)



Orbit Misclosures: ECOM-plus-boxwing (1-day solutions)



Orbit Misclosures: ECOM-plus-scaled-boxwing



Conclusions & Future Work

Conclusions

- Able to stack scale factors for long periods of time
- Able to distinguish/validate thermal re-radiation
- Number of scale factors per satellite depends on characteristics
- Improvements at the daily solution level

Forward Work



QUESTIONS?